

# Designing Yellow Intervals for Rainy and Wet Roadway Conditions

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## ABSTRACT

The research presented in this paper quantifies and models the impact of wet pavement surface and rainy weather conditions on driver perception-reaction times (PRTs), deceleration levels, and traffic signal change interval durations. A total of 648 stop-run records were collected as part of the research effort for a 72 km/h (45 mi/h) approach speed where participant drivers encountered a yellow indication initiation at different distances from the intersection. The participant drivers were randomly selected in different age groups (under 40 years old, 40 to 59 years old, and 60 years of age or older) and genders (female and male). Using the gathered data, statistical models for driver PRT and deceleration levels were developed, considering roadway surface and environmental parameters, driver attributes (age and gender), roadway grade, approaching speed, and time and distance to the intersection at the onset of yellow. Inclement weather yellow timings were then developed and summarized in lookup tables as a function of different factors (driver

age/gender, roadway grade, speed limit, precipitation level, and roadway surface condition) to provide practical guidelines for the design of yellow signal timings in wet and rainy weather conditions. The results indicate that wet roadway surface conditions require a 5 percent increase in the change interval and that rainy conditions require a 10 percent or more increase in the duration of the change interval. These recommended change durations can also be integrated within the Vehicle Infrastructure Integration (VII) initiative to provide customizable driver warnings prior to a transition to a red indication.

## INTRODUCTION

Red-light running is one of the most common causes of intersection crashes. The generally accepted definition of the yellow change interval is to warn motorists that the related green movement is being terminated or that a red signal indication will be exhibited immediately thereafter. Some jurisdictions supplement the yellow interval with an all-red interval to provide additional clearance time to clear the intersection of all vehicles that entered the intersection legally during the yellow interval. Interval duration is a significant factor affecting the frequency of red-light running, yet there remains no national consensus on how the yellow and all-red intervals should be timed for safe and efficient operations.

Studies of driver reaction times and vehicle deceleration rates used in determining appropriate yellow and all-red change intervals were conducted more than 25 years ago, although some recent studies have occurred in the past couple of years. Additional studies are needed to validate whether these driver reaction times and deceleration rates are still appropriate. It is not clear at this time what impact inclement weather and roadway conditions have on traffic signal clearance times. Consequently, the objective of this study is to characterize the impact of roadway surface and rainy weather conditions on driver perception reaction times (PRTs) and deceleration levels for the design of traffic signal change intervals. These changes in behavior are integrated into the design procedures of yellow timings to reflect the current roadway surface and weather conditions. The clearance timings are found to be significantly different and thus alternative yellow and clearance times should be incorporated within traffic signal controllers. One possibility is to store an inclement weather traffic signal plan in controllers that can be initiated when weather conditions warrant the implementation of this plan.

In terms of the paper layout, the following section provides a brief background of the problem. Subsequently, the data collection experimental design and procedures are described followed by a quantification of roadway surface and weather conditions on driver PRT and deceleration levels. Lookup tables are then developed for the design of yellow timings. Finally, the study conclusions and recommendations for further research are presented.

## BACKGROUND

Vehicle crashes typically happen due to driver violations of traffic signalized intersections. Studies have shown that drivers violate the red signal light every 20

minutes on average at each intersection, and this violation rate is even higher during peak hours [1]. According to the Insurance Institute for Highway Safety, 762 people were killed and about 137,000 injured in crashes that involved red-light running in 2008[2].

The yellow signal interval is designed to warn approaching drivers of an impending loss of right-of-way for the traffic crossing a signalized intersection in the previous green signal indication. When a yellow indication is triggered, the driver determines whether to stop safely or to proceed through the intersection before the end of the yellow interval. Incorrect driver decisions may result in either a rear-end collision if the driver decelerates at a sudden high rate, or a straight-crossing-path crash if the driver does not have enough time to safely cross the intersection before the conflicting flow is released.

The dilemma zone problem has been examined in the literature since its initial formulation in [3], who observed the existence of dilemma zones at approaches to signalized intersections and developed the first dilemma zone model, as a binary decision problem to either stop or proceed when a yellow indication is triggered. However, an analysis of the literature demonstrates a lack of consensus in defining the dilemma zone. For example, the dilemma zone was defined “as that zone within which the driver can neither come to a safe stop nor proceed through the intersection before the end of the yellow phase” [4]. This definition represents the design definition of a dilemma zone. Alternatively, others define the dilemma zone (also called the decision zone) from a driver’s perspective as the zone in which between 10 to 90 percent of the drivers stop [5]. The approach of modeling this problem was summarized in [4] as “developing dilemma zone curves of ‘percent drivers stopping’ versus ‘distance from stop bar’ at the instant when the signal indication changes from green to yellow” and that the driver behavior at high-speed signalized intersections when faced with a yellow indication can be viewed as a binary choice process, in which the relevant decisions are either to stop or proceed through the intersection.

Several research efforts have attempted to develop methods to decrease the possibility of being caught in the dilemma zone following this issue raised. Theoretically, according to [6], when a vehicle is under the speed limit while approaching the signalized intersection, the dilemma zone can be totally eliminated by acceleration beyond a certain critical value or following a linear functional form. However, it is obviously inappropriate to urge drivers to accelerate blindly when they find themselves trapped in the dilemma zone. In terms of traffic signal design, a proper clearance interval can minimize or eliminate the number of drivers caught in dilemma zones [7].

Currently the commonly used method to compute the intervals is the ITE formula[8]. Equation(1) is the ITE formula based on the kinematic model of vehicles’ deceleration times at intersections.

$$y = t + \frac{v_0}{2(a + 9.81G)} + \frac{x + L}{v_0} \quad (1)$$

Where  $y$  is the yellow interval duration (s),  $t$  is driver PRT (s),  $a$  is the constant

deceleration level ( $\text{m/s}^2$ ),  $v_0$  is the constant approach speed ( $\text{m/s}$ ),  $G$  is the roadway grade (decimal),  $w$  is the effective intersection width ( $\text{m}$ ), and  $L$  is the length of the vehicle ( $\text{m}$ ). The term  $(w + L)/v_0$  is only used when there are no all-red intervals.

Improvements to the traffic signal clearance times enhances the safety of the intersection[9]. A study in [10] conducted at an intersection concluded that the crash rate for the drivers group with the least adequate clearance intervals was significantly higher than that of the drivers group with the most adequate intervals. An urban intersection study[11] involving changes in signal timing at 10 intersections indicated that change intervals set closer to ITE's proposed recommended practice can reduce red-light violations. A study by Bonneson and Zimmerman[12] found that an increase of 1.0s in the yellow duration (for a maximum of 5.5s) will decrease the frequency of red-light running by at least 50 percent, while drivers' adaption to the change does not undo the benefit. On the other hand, long yellow timing may be treated as an extension of green by the drivers, which may lead to the loss of yellow indication meaning[7]. Alternatively, longer clearance intervals may incur additional vehicle delays and emissions.

Weather has effects on roadway mobility, safety, and efficiency. A study conducted under inclement weather conditions in Salt Lake City collected more than 30 hours of speed, flow rate, and start-up delay data in 14 days[13]. Start-up delay increased by 5 and 23 percent, respectively on wet and snowy pavements compared to behavior on dry pavements. A traffic simulation model was developed for a nine-intersection corridor in downtown Salt Lake City and demonstrated that travel time would rise by 50 percent and that vehicle stops would increase by 14 percent if normal signal timing plans were utilized in inclement conditions. Another study measured signal timing plan parameters in summer, winter, and extreme conditions in Anchorage, Alaska[14]. It found a 20 percent reduction in flow rates and demonstrated that signal timing parameters used in the summer were not appropriate for winter or extreme conditions. Perrin *et al.* collected traffic flow data over a range of seven inclement weather severity conditions at two intersections during the 1999–2000 winters in Salt Lake City[13]. This study documented conclusions for modifying parameters in developing new inclement weather timing plans including: an increase in yellow time by 10 to 15 percent (0.5 to 1 s) depending on the intersection size; an increase in the all-red time by 1 s to account for the slower clearing of the intersection by “sneakers” at permitted or protected intersections (taking 0.75 s longer than during clear conditions); and an increase in clearance intervals even further at intersections where there is high speed or steep grade approaches.

Several state DOT agencies (such as Maryland, Ohio, Minnesota etc.) have attempted to implement inclement weather signal timings but few of them found recommendations for changes in the signal timings during inclement weather [15]. A review of the literature revealed very limited research studying the impacts of inclement weather and roadway conditions on traffic signal timings. Consequently, it is necessary to observe and characterize driver behavior under inclement weather conditions in order to design signal timing plans for inclement weather and road conditions.

## EXPERIMENTAL DESIGN

In a previous study [16] conducted by the same research group, a field data collection effort was conducted to characterize driver PRT and deceleration behavior at the onset of a yellow indication as a function of various driver and traffic stream characteristics under clear weather conditions. The test conditions were based on two different instructed speeds (72 km/h and 89 km/h) and three different platooning conditions (leading, following and no other vehicles).

The field experiment described in this paper was conducted at the same location as the previous study, namely the Virginia Department of Transportation's (VDOT) Smart Road facility. The major difference is that all tests were conducted under rainy weather conditions with wet pavement surfaces. All tests were executed at an instructed speed of 72km/h with no leading/following vehicles because the previous study did not find the lead or following vehicle to have a statistically significant impact on driver stop/go decisions, PRTs, and deceleration levels.

### Test Facility

The field experiment was designed to collect field data of driver behavior under wet pavement surface and rainy weather conditions at the VDOT's Smart Road. The Smart Road is a unique, state-of-the-art, full-scale, closed test-bed research facility, located at the Virginia Tech Transportation Institute (VTTI), owned and maintained by VDOT. The Smart Road is a 3.5 km (2.2 mi) two-lane road with one four-way signalized intersection, as illustrated in Figure 1. The section used for the data collection includes only the section between two turnarounds with the four-way signalized intersection. The first turnaround is a high-speed banked turnaround at one end and the second is a medium-speed speed flat turnaround at the other end. The intersection consists of two high-speed approaches and two low-speed approaches and is outfitted with customized controllers and vehicle presence sensors, as well as wireless communications. The horizontal layout of the experiment section is fairly straight with some minor horizontal curvatures which do not impact vehicles' speed and provides good visibility of front view. The vertical layout of the experiment section has a substantial grade of 3 percent [17]. The participant drivers drove from the first turnaround and turned around on the second turnaround, so half the trails were on a 3percent upgrade and the other half were on a 3percent downgrade.

### Experimental Equipment

A 1997 Ford Taurus, driven by participant drivers (accompanied by a research assistant), was used in the experiment, as illustrated in Figure 1. It was equipped with a Differential Global Positioning System (DGPS), a real-time data acquisition system (DAS), and a laptop with a program installed to control the trials. The DAS was capable of collecting data at 0.1-second intervals and was located inside the vehicle's trunk and out of the view of the test subject. During the experiment, the following attributes could be seen from the in-vehicle laptop interface: current subjects' number and age, current order /trail number, current signal phase (green, yellow, or red), time remaining in the signal (green, yellow, or red) interval, current distance to the intersection stop bar (DTI),

current travel time to the intersection (TTI) based on the current vehicle speed and current distance to the intersection stop bar, and windshield wiper speeds (6 levels from 0 to 5). All data were recorded and stored in the data recording instrumentation installed in the test vehicle's trunk. The data recording equipment had a communication link to the intersection signal control box so the vehicle data and the traffic signal data could be synchronized. Two video cameras were used, one was a digital color camera recording the front view of the test vehicle and the other video camera was used to record continuously the participant's foot movements.



Figure 1. Instrumented vehicle and field test site

Another vehicle, a 1996 Oldsmobile Aurora, was driven by another research assistant as a confederate vehicle to simulate the side-street traffic typical in a real-world environment. The confederate vehicle crossed the intersection legally from the conflicting approach of the test vehicle. It entered the roadway only when the traffic light was green and the subject vehicle was completely stopped. Both vehicles were equipped with a communication system, to be operated by the research assistants, between the two vehicles and the Smart Road control tower. The experiment included only scenarios with participants driving the vehicle straight through the intersection with no turning movements.

## PARTICIPANTS

To protect the rights of and ensure the safety of human subjects participating in the research, approval was obtained in October, 2009 from Institutional Review Board (IRB) at Virginia Tech before recruiting the participant drivers.



Participant drivers were screened through an oral questionnaire to determine whether they were licensed drivers and whether they had any health concerns that would exclude them from participating in the study. Volunteers were paid \$20 per hour for a 1 to 1.5 hour session. A total of 27 participant drivers were recruited in three age groups, nine of whom were under 40-years-old, ten drivers between 40 to 59 years old, and 8 drivers were 60 years of age or older. Near equal numbers of males and females were assigned to each group. Participant drivers were tested individually with an researcher present in the vehicle at all times during the study to provide instructions, operate the computer system, supervise the experiment, and answer any questions. The existence of the researcher did not seem to impact the driver behavior because the results that were derived (presented later in the paper) were consistent with the findings in the Salt Lake City study that was described earlier [13].

## **Procedure**

Testing was conducted under rainy weather and wet pavement surface conditions. On arrival at VTTI, each participant was asked to review and sign an informed-consent form and complete a medical questionnaire to verify that he or she did not have any medical conditions that would impair his or her ability to drive.

Before the first trial, the participant drivers were allowed to familiarize themselves with the Smart Road test facility by driving several loops and passed the intersection several times. Exclusive of practice trials, the participant drove the entire test loop 24 times for a total of 48 trials and was instructed to cruise at a speed of 72 km/h (45 mi/h) while approaching the signalized intersection and to obey all traffic laws. One trial consisted of one approach to the intersection.

Among the 48 trials, there were 24 trials in which the yellow indications were triggered for 4 repetitions at 6 different distances to intersection. The yellow indications were triggered when the front of the test vehicle was 54.3, 62.5, 70.4, 76.5, 82.6, and 92.7 m (178, 205, 231, 251, 271, and 304 ft) from the intersection. On the remaining 24 trials the signal indications remained green. This scheme resulted in yellow/red signals being presented on 50 percent of the 48 trials; conversely, 50 percent of the 48 trials consisted solely of green signal indications. The yellow-light duration was 4-seconds. In the trials in which the yellow indications were triggered, outputs from the radar triggered the phase change at different distances to the intersection following a preset random order. It should be noted that the sequence of triggers and green indications were totally random.

## **FIELD DATA ANALYSIS**

More than 30 participant drivers participated in the experiment. Due to the unpredictability and sudden changes in the weather conditions, some tests were canceled halfway and those recorded data were excluded from the analysis. A total of 648 records for 27 participant drivers were available for analysis, including 453 stopping records and 195 running records. For each trial, the real-time data were tracked and recorded every deci-second, 250m before and after the signalized intersection.

### Approach Speed at the Onset of Yellow

As mentioned earlier, participants were instructed to cruise at a speed of 72 km/h (45 mi/h) while approaching the signalized intersection. However, drivers' momentary approach speeds to the intersection ranged from a minimum of 56.84 km/h (35.32 mi/h) to a maximum of 84.75 km/h (52.66 mi/h), with a median of 74.61 km/h (46.36 mi/h) and a mean of 74.21 km/h (46.11 mi/h). The histogram of the approach speeds at the onset of yellow indications is presented in Figure 2. The histogram demonstrates a bias towards the higher speed range.

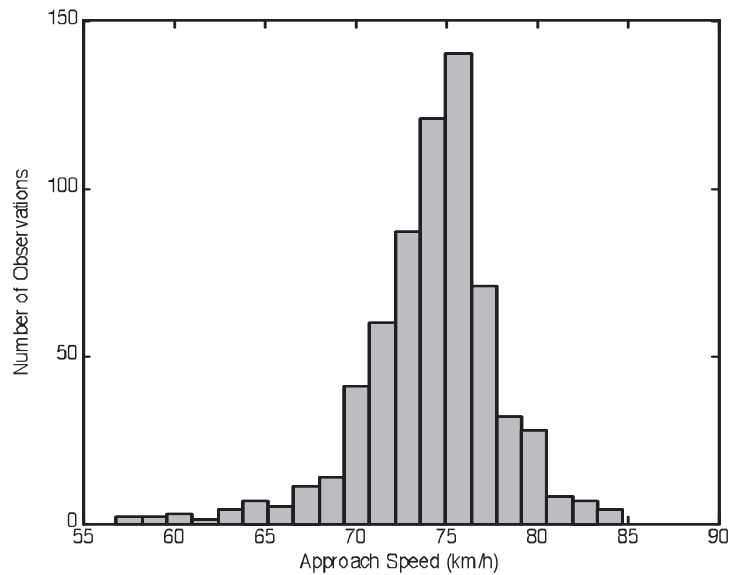


Figure 2. Histogram of Approach Speed at the Onset of Yellow

### Probability Distribution of Stopping/Running Decision

The average probabilities are sorted into equal sized bins with an equal number of observations in each bin based on driver's TTI at the onset of the yellow signal indication. The 90% probability of stopping (10% probability for running) point occurs between 4.0 and 4.2 s from the stop line at the onset of the yellow indication. Compared to results between 3.6 s and 3.8 s in clear weather condition in the previous study[18], the 0.9/0.1 stopping/running probability is obviously longer in rainy weather conditions, which indicates that the driver dilemma zone (decision zone) boundaries start at a longer distance from the stop line in rainy weather conditions. The shift of the decision zone boundaries is about 0.2 s, which is 3.7m (12 ft) from stop bar, for the 72 km/h instructed speed. This trend is larger than the findings in an earlier study[19], which demonstrated that the start of dilemma zone boundaries shifts farther by approximately 2ft for all speeds in case of rain.



### Analysis of Yellow/RedLightRunning Behavior

To examine drivers' behavior after the running decision at the yellow indication, a scatter diagram is plotted between the vehicles' TTIs at the onset of yellow indications and their entry times. The entry time is defined as the elapsed time between the onset of yellow indication and the instant the vehicle traverses the stop line. TTI is computed as the vehicle's instantaneous distance to the stop bar (DTI)divided by the instantaneous speed at the onset of yellow. If the driver accelerates to ensure crossing the intersection without encountering a red, the entry time would be shorter than the TTI. On the contrary, if the driver slows down, the entry time would be longer than the TTI. The scattered points were found to follow a trend line with a slope of 1.0 and the intercept of 0.0. The trend line demonstrates that most drivers neither accelerate nor decelerate while running at the onset of a yellow indication. It can also be inferred that even for the red light signal violations, most drivers do not intentionally violate the red but fail to make the correct judgment. This phenomenon is consistent in both rainy and clear weather conditions.

### Analysis of Yellow/Red Light Stopping Behavior

PRT is defined as the time between the onset of yellow indication and the instant the driver starts pressing the brake pedal. It includes the mental processing time (perception time) and the movement time (reaction time). Although there were 453 stopping records, 51 of the records showed that the driver had already released the accelerator before the onset of the yellow indication. These records were not counted as valid PRT since they do not include the reaction time (the foot movement time from the accelerator to the brake pedal). A total of 402 valid PRTs were available from the data records. The PRTs ranged between a minimum of 0.40s to a maximum of 1.80s, with a median of 0.80s and a mean of 0.85s.

Compared with the 337 PRT records from the previous study under clear weather conditions which had a median of 0.72s and a mean of 0.74s, the apparent increase in PRTs indicates that drives' PRTs in rainy weather conditions tend to be longer. Possible explanations for the above phenomenon are: (1) invisibility of the signal lights with raindrops on the front window and mist in the air or (2) longer decision-making time because of the increased complexity in making a decision. The comparison of empirical cumulative distribution functions (CDF) of PRTs between clear and rainy weather conditions are plotted in Figure 3. The Kolmogorov-Smirnov test (KS-test) was conducted to compare the two PRT datasets (dry and wet), as illustrated in Figure 3. The P-value approximately equals to 0 ( $4.0e^{-44}$ ) and the maximum difference between two curves equals to 0.5189. The result of the KS-test indicates the significant difference in driver PRTs between clear and rainy weather conditions, as is evident in Figure 3.

As described earlier, the instantaneous speeds were recorded every deci-second as well as the drivers' foot movements and brake pedal positions. The average deceleration level was computed as,

$$d_{avg} = \frac{v_0 - v_1}{t_0 - t_1} \quad (2)$$

where  $v_0$  is the vehicle speed when the driver pressed the brake pedal after the onset of a yellow indication,  $v_f$  is the final vehicle speed of the stopping action (when the speed is less than 1 m/s),  $t_0$  is the instant in time when the driver pressed the brake pedal after the onset of a yellow indication and  $t_f$  is the instant in time when the final speed was achieved.

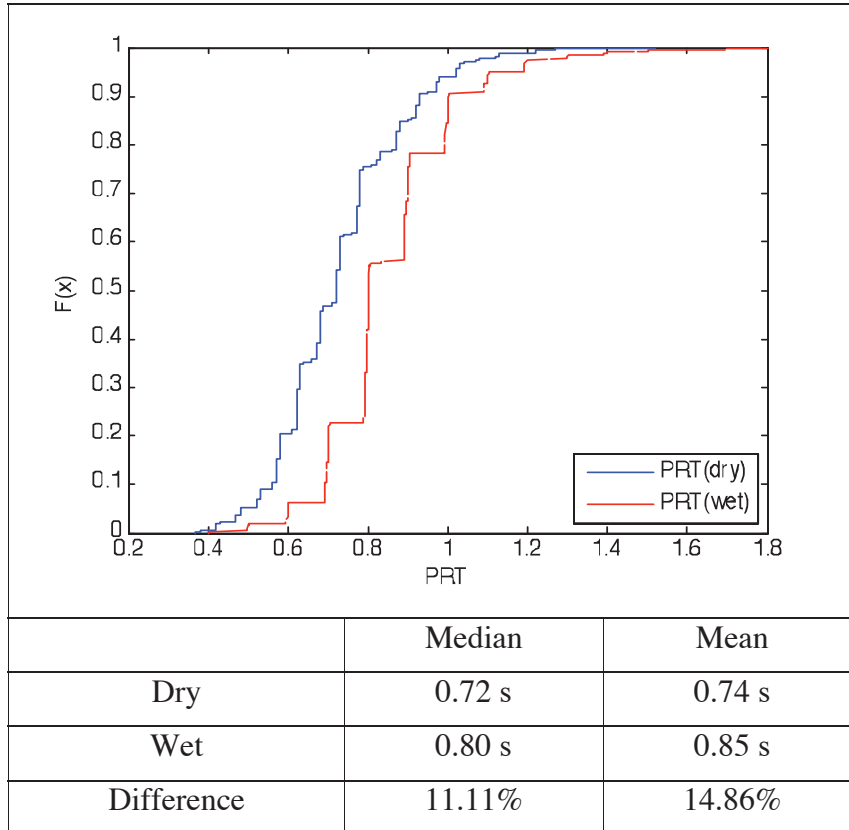


Figure 3. CDF of Driver Perception-Reaction Times

A total of 402 valid observations were available to compute the deceleration levels in wet weather conditions. The deceleration levels ranged from a minimum of  $1.43 \text{ m/s}^2$  to a maximum of  $6.41 \text{ m/s}^2$ , with a median of  $3.30 \text{ m/s}^2$  and a mean of  $3.44 \text{ m/s}^2$ . Under clear weather condition, the deceleration levels ranged from  $2.31 \text{ m/s}^2$  to  $7.31 \text{ m/s}^2$  ( $24 \text{ ft/s}^2$ ) with a median of  $3.55 \text{ m/s}^2$  and a mean of  $3.70 \text{ m/s}^2$  [16]. The mean deceleration of wet and rainy weather conditions decreased by approximately 8% compared to the clear weather condition. In an earlier study by Kulakowski, results indicated that as little as 0.05 mm (0.002 in.) of water on a pavement surface could reduce tire-pavement friction by 20 – 30% of the dry surface friction at 64 km/h (40 mi/h). The reduction of friction

would be greater with increase of speed, and varies by pavement surface material and tire types[20]. Compared to these findings, the 8% reduction in deceleration levels implies a more aggressive deceleration behavior of drivers (e.g. pressing the brake pedal harder) under rainy weather conditions, and this behavior change does not eliminate the effects of friction reduction on wet pavement surface. AKS-test was conducted to compare the deceleration levels from the two datasets (dry and wet), as illustrated in Figure 4. The KS-test result indicates a significant decrease in deceleration levels between clear and rainy weather conditions, with a P-value equal to 0.00001. The maximum difference between the two curves equals to 0.1792.

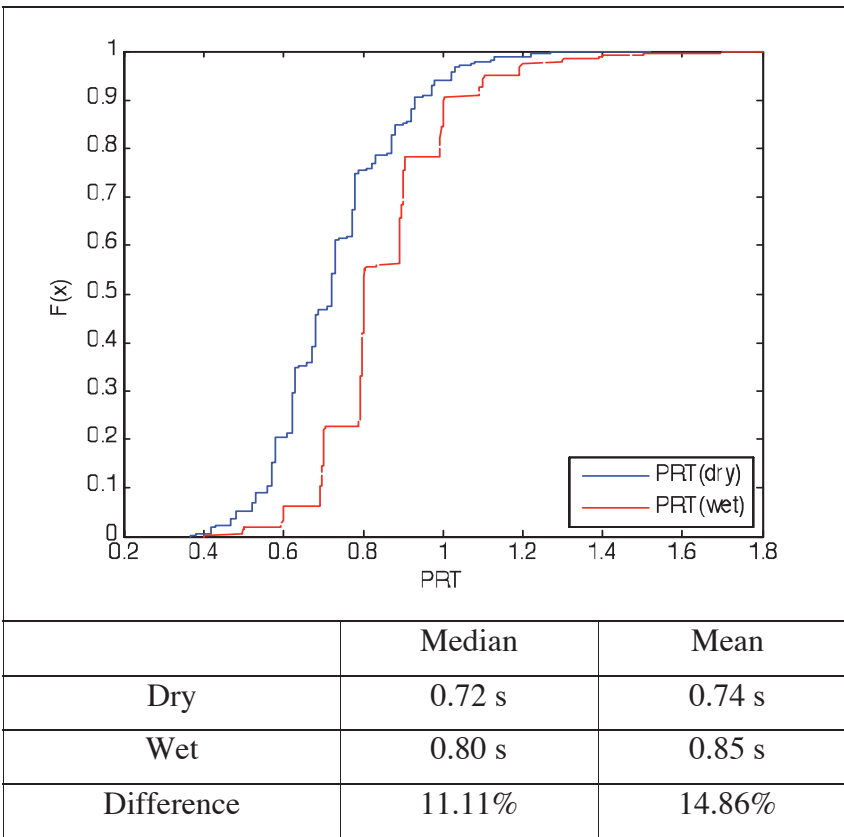


Figure 4. CDF of Drivers' Deceleration Levels

### YELLOW TIMING MODELING IN RAINY WEATHER CONDITIONS

According to the Institute of Transportation Engineers (ITE) formula, the yellow interval duration is computed as,

$$y = t + \frac{v_0}{2a + 2 \times 9.81G} \quad (3)$$

where  $y$  is the yellow interval duration (s),  $t$  is driver PRT (s),  $a$  is the constant deceleration level ( $\text{m/s}^2$ ),  $v_0$  is the constant approach speed ( $\text{m/s}$ ),  $G$  is the roadway grade (decimal).

The modeling of driver PRTs and the deceleration levels when they encounter a yellow indication for both clear and rainy weather conditions are developed using the available data from both the previous and the current field tests.

### Modeling of Driver PRT

In addition to the contributory factors of the PRT including drivers' physical characteristics (gender and age), pavement features (grade), and vehicles' physical states (TTI, speed), a term of rainfall precipitation level  $P$  is added to examine the effect of rain on the PRT. The binary variable  $P$  is set equal to zero when the weather is clear, equal to 1 when the pavement surface is wet but the rainfall is very light, and equal to 2 when the rainfall is significant. Considering the possible interactive effects between the factors, cross terms were also included. The statistical method of stepwise regression modeling was used using the JMP 8 software to fit a model to the data. Setting the confidence level as 95%, the final significant variables and their cross terms are shown Equation (4).

$$t = b_0 + b_1g + b_2s + b_3G + b_4 \frac{TTI}{y} + b_5 \frac{v}{v_f} + b_6p + b_7g \frac{v}{v_f} + b_8G \frac{v}{v_f} + b_9 \frac{v}{v_f} p + err_t \quad (4)$$

Where  $t$  is the perception-reaction time (s),  $b_i$  s are model coefficients,  $g$  is the driver gender (0 male and 1 female),  $s$  is the driver age (years),  $G$  is the roadway grade (percent/100),  $TTI$  is the time-to-intersection at the onset of the yellow indication (s),  $y$  is the yellow interval duration (s),  $v$  is the approaching speed and  $v_f$  is the instructed speed ( $\text{km/h}$ ),  $p$  is the precipitation level (0: clear, 1: wet surface/ very light rain, 2: rainy), and  $err_t$  is the term of random error.

The final form of the PRT model is shown in Equation (5). All variables in the model were statistically significant. The PRT residuals were found to follow the normal distribution and were within  $[-1, 1]$ , which implies no outliers of the data were used. The adjusted  $R^2$  was 0.22, which is reasonable for predicting human behavior. In addition, there is a good relation between the PRT and each of the explanatory variables with  $p$ -values of less than 0.05.

$$t = 1.4995 - 0.8400g + 0.0008s - 11.5464G + 0.2728 \frac{TTI}{y} - 1.0422 \frac{v}{v_f} - 0.4367p + 0.8450g \frac{v}{v_f} + 12.5101G \frac{v}{v_f} + 0.4779 \frac{v}{v_f} p + err_t \quad (5)$$

### Modeling of Driver Deceleration Behavior

A previous study [21] suggested that for signal change interval design, joint consideration instead of independent consideration should be given to PRTs and

deceleration levels when selecting their values. In addition, the study suggested that different PRTs and deceleration levels should be considered for different approach speeds rather than a single value (as used in the current practice). Consequently, the PRT is added as an explanatory variable in addition to the driver gender and age, the pavement grade, the vehicle TTI and speed, and the precipitation flag.

By applying the stepwise regression function in JMP 8 to fit a model to the data, the significant variables at the 95% confidence level are shown in Equation (6).

$$d = b_0 + b_1g + b_2s + b_3G + b_4 \frac{TTI}{y} + b_5 \frac{v}{v_f} + b_6p + b_7t + b_8 \left( \frac{TTI}{y} \right)^2 + b_9ga + b_{10} \frac{TTI}{y} p + err_d \quad (6)$$

Here  $d$  is the deceleration level ( $m/s^2$ ),  $b_i$  s are calibrated model coefficients,  $g$  is the driver gender (0 male and 1 female),  $s$  is the driver age (years),  $G$  is the roadway grade (percent/100),  $TTI$  is the time-to-intersection at the onset of the yellow indication (s),  $y$  is the yellow time (s),  $v$  is the approaching speed and  $v_f$  is the instructed speed (km/h),  $p$  is the precipitation level (0: clear, 1: wet surface/ very light rain, 2: rainy), and  $err_d$  is the term for random error.

The calibrated coefficients and corresponding  $p$ -values were computed. The final form of deceleration level model was of the form of Equation (7). The results of the statistic modeling indicate that there are explanatory relationships between deceleration levels and gender, age, grade, TTI, speed, precipitation, PRT,  $TTI^2$ , and the cross-product of gender and age, TTI and precipitation. The adjusted  $R^2$  is 0.88, which is a good indication of the model.

$$d = 10.6577 - 0.2782g - 0.0079s - 2.0816G - 20.0664 \frac{TTI}{y} + 3.6821 \frac{v}{v_f} + 0.2136p + 1.4376t + 8.0828 \left( \frac{TTI}{y} \right)^2 + 0.0046ga - 0.2934 \frac{TTI}{y} p + err_d \quad (7)$$

### Yellow Timing Modeling

The variables used in the ITE procedures for computing yellow interval duration include the driver PRT and deceleration levels. With these dependent variables, the yellow interval timing can be adjusted to model various combinations of driver gender and age groups, roadway grade, time to the intersection at the onset of yellow indication, approach speed and speed limit. The method of Monte Carlo Simulation is used to generate random combinations of independent and dependent variables and compute the corresponding yellow timing using Equation (3). The yellow timing thus becomes a stochastic variable and can then be used to compute the yellow timing for a desired level of reliability.

The individual variables are randomly selected and a sample of 100,000 drivers is simulated in MATLAB. The discrete uniform random number generator is used for

drivers' age (from 20 to 79 years old), drivers' gender (as 0-1 distribution), roadway grade (from -4% to 4%) and precipitation levels (0: clear, 1: wet pavement surface/very light rain, 2: rainy). The continuous uniform random number generator is used for TTIs at the onset of the yellow indication (slightly larger than the dilemma zone boundaries under specific weather conditions at the instructed speed). The empirical distribution is used in the Monte Carlo Simulation process to generate the approach speed.

Results from the Monte Carlo Simulation demonstrate that during rainy weather conditions, the yellow intervals should be longer than those in clear weather conditions. According to the Kolmogorov-Smirnov KS-test, the difference of yellow timing distributions for the three weather conditions is highly significant ( $p$ -value = 0). Higher yellow duration time is needed for higher speed limits and lower roadway grades. Furthermore as the precipitation level increases the necessary yellow duration also increases.

### LOOK-UP TABLES FOR YELLOW CLEARANCE INTERVALS

Look-up tables are generated, to compute the yellow time duration, using the Monte Carlo simulation results. As an example, the look-up tables include three speed limits (56, 72, and 88 km/h) which correspond to 35, 45, and 55 mi/h, nine roadway grades (ranging from -4 to 4 percent), three weather conditions (clear, wet pavement surface/very light rain, rainy) and 12 reliability levels (ranging from 50 to 99.9 percent).

For the three precipitation levels used in the study, the required increase in yellow interval timing from clear conditions to wet roadway surface conditions is between 4 to 7 percent and the required increase for rainy conditions is about 9 to 15 percent at different reliability levels ranging from 50 to 99.9 percent. These results are consistent with an earlier study that found differences in yellow times ranging from 10 to 15 percent [13].

The results demonstrate that with a higher precipitation level, a longer yellow interval duration is needed. From clear weather to very light rain weather conditions, the required yellow timing at 85 percent reliability increases by approximately 5 percent. When the weather is rainy, another 5 to 7 percent increase is necessary. The results also show that the percentage increase in yellow interval durations decreases as the roadway grades increases.

Higher reliability levels require longer yellow interval durations, which provide more safety to the drivers and reduce the probability of being exposed to the design dilemma zone. But shorter yellow intervals could be more economic, time saving and environmentally friendly. In order to get a better understanding of the trade-off between in these considerations, look-up tables are generated, as shown in Tables 5 through 7, for several reliability levels for the computation of yellow interval durations.

**Table 1. Proposed Yellow Interval Durations for 56 km/h Speed Limit (35 mi/h)**

Grade	-4%			-3%			-2%		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	2.6	2.8	3.0	2.6	2.8	3.0	2.6	2.7	2.9
60%	2.9	3.1	3.4	2.9	3.1	3.3	2.8	3.0	3.2
70%	3.2	3.4	3.7	3.2	3.4	3.6	3.1	3.3	3.5
80%	3.5	3.7	4.0	3.4	3.7	3.9	3.4	3.6	3.8
85%	3.7	3.9	4.1	3.6	3.8	4.0	3.5	3.7	3.9
90%	3.8	4.0	4.3	3.7	3.9	4.1	3.6	3.8	4.0
95%	3.9	4.2	4.4	3.8	4.0	4.3	3.7	3.9	4.2
96%	4.0	4.2	4.4	3.9	4.1	4.3	3.8	4.0	4.2
97%	4.0	4.2	4.5	3.9	4.1	4.3	3.8	4.0	4.2
98%	4.0	4.3	4.5	3.9	4.2	4.4	3.8	4.0	4.3
99%	4.1	4.3	4.6	4.0	4.2	4.5	3.9	4.1	4.3
99.9%	4.2	4.5	4.8	4.1	4.4	4.7	4.0	4.2	4.5

Grade	-1%			0 %			1 %		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	2.5	2.7	2.9	2.5	2.7	2.9	2.5	2.7	2.8
60%	2.8	3.0	3.2	2.8	2.9	3.1	2.7	2.9	3.1
70%	3.0	3.2	3.4	3.0	3.2	3.4	3.0	3.1	3.3
80%	3.3	3.5	3.7	3.2	3.4	3.6	3.2	3.4	3.6
85%	3.4	3.6	3.8	3.3	3.5	3.7	3.3	3.5	3.7
90%	3.5	3.7	3.9	3.4	3.6	3.8	3.4	3.6	3.8
95%	3.6	3.8	4.0	3.6	3.7	3.9	3.5	3.7	3.9
96%	3.7	3.9	4.1	3.6	3.8	4.0	3.5	3.7	3.9
97%	3.7	3.9	4.1	3.6	3.8	4.0	3.5	3.7	3.9
98%	3.7	3.9	4.2	3.6	3.8	4.0	3.6	3.7	3.9
99%	3.8	4.0	4.2	3.7	3.9	4.1	3.6	3.8	4.0
99.9%	3.9	4.1	4.4	3.8	4.0	4.3	3.7	3.9	4.2

Grade	2 %			3 %			4 %		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	2.5	2.6	2.8	2.4	2.6	2.8	2.4	2.6	2.7
60%	2.7	2.9	3.0	2.7	2.8	3.0	2.6	2.8	3.0
70%	2.9	3.1	3.3	2.9	3.0	3.2	2.8	3.0	3.2
80%	3.1	3.3	3.5	3.1	3.2	3.4	3.0	3.2	3.4
85%	3.2	3.4	3.6	3.2	3.3	3.5	3.1	3.3	3.4
90%	3.3	3.5	3.7	3.3	3.4	3.6	3.2	3.4	3.5
95%	3.4	3.6	3.8	3.3	3.5	3.7	3.3	3.4	3.6
96%	3.4	3.6	3.8	3.4	3.5	3.7	3.3	3.5	3.6
97%	3.5	3.6	3.8	3.4	3.6	3.7	3.3	3.5	3.7
98%	3.5	3.7	3.8	3.4	3.6	3.8	3.4	3.5	3.7
99%	3.5	3.7	3.9	3.5	3.6	3.8	3.4	3.6	3.7
99.9%	3.6	3.8	4.1	3.5	3.7	4.0	3.5	3.7	3.9



**Table 2: Proposed Yellow Interval Durations for 72 km/h Speed Limit (45 mi/h)**

Grade	-4%			-3%			-2%		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	3.2	3.4	3.6	3.1	3.3	3.5	3.1	3.3	3.4
60%	3.5	3.7	3.9	3.4	3.6	3.8	3.3	3.5	3.7
70%	3.8	4.0	4.2	3.7	3.9	4.1	3.6	3.8	4.1
80%	4.1	4.3	4.6	4.0	4.2	4.5	3.9	4.1	4.4
85%	4.2	4.5	4.8	4.1	4.4	4.6	4.1	4.3	4.5
90%	4.4	4.7	4.9	4.3	4.5	4.8	4.2	4.4	4.7
95%	4.6	4.8	5.1	4.5	4.7	5.0	4.3	4.6	4.8
96%	4.6	4.9	5.1	4.5	4.7	5.0	4.4	4.6	4.9
97%	4.7	4.9	5.2	4.5	4.8	5.0	4.4	4.6	4.9
98%	4.7	5.0	5.3	4.6	4.8	5.1	4.5	4.7	5.0
99%	4.8	5.0	5.4	4.6	4.9	5.2	4.5	4.8	5.0
99.9%	4.9	5.2	5.6	4.8	5.1	5.4	4.7	4.9	5.3

Grade	-1%			0%			1%		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	3.0	3.2	3.4	3.0	3.2	3.4	3.0	3.1	3.3
60%	3.3	3.5	3.7	3.2	3.4	3.6	3.2	3.4	3.6
70%	3.6	3.8	4.0	3.5	3.7	3.9	3.5	3.6	3.8
80%	3.8	4.1	4.3	3.8	4.0	4.2	3.7	3.9	4.1
85%	4.0	4.2	4.4	3.9	4.1	4.3	3.8	4.0	4.2
90%	4.1	4.3	4.5	4.0	4.2	4.4	3.9	4.1	4.3
95%	4.2	4.5	4.7	4.1	4.3	4.6	4.1	4.3	4.5
96%	4.3	4.5	4.7	4.2	4.4	4.6	4.1	4.3	4.5
97%	4.3	4.5	4.8	4.2	4.4	4.6	4.1	4.3	4.5
98%	4.3	4.6	4.8	4.2	4.5	4.7	4.1	4.4	4.6
99%	4.4	4.6	4.9	4.3	4.5	4.8	4.2	4.4	4.6
99.9%	4.5	4.8	5.1	4.4	4.7	5.0	4.3	4.5	4.8

Grade	2%			3%			4%		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	2.9	3.1	3.3	2.9	3.1	3.2	2.9	3.0	3.2
60%	3.2	3.3	3.5	3.1	3.3	3.5	3.1	3.2	3.4
70%	3.4	3.6	3.8	3.3	3.5	3.7	3.3	3.5	3.6
80%	3.6	3.8	4.0	3.6	3.7	3.9	3.5	3.7	3.9
85%	3.7	3.9	4.1	3.7	3.9	4.0	3.6	3.8	4.0
90%	3.9	4.0	4.2	3.8	4.0	4.2	3.7	3.9	4.1
95%	4.0	4.2	4.4	3.9	4.1	4.3	3.8	4.0	4.2
96%	4.0	4.2	4.4	3.9	4.1	4.3	3.8	4.0	4.2
97%	4.0	4.2	4.4	3.9	4.1	4.3	3.9	4.0	4.2
98%	4.1	4.3	4.5	4.0	4.2	4.4	3.9	4.1	4.3
99%	4.1	4.3	4.5	4.0	4.2	4.4	3.9	4.1	4.3
99.9%	4.2	4.4	4.7	4.1	4.3	4.6	4.0	4.2	4.5

**Table 3. Proposed Yellow Interval Durations for 88 km/h Speed Limit (55 mi/h)**

Grade	-4%			-3%			-2%		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	3.2	3.4	3.6	3.1	3.3	3.5	3.1	3.3	3.4
60%	3.5	3.7	3.9	3.4	3.6	3.8	3.3	3.5	3.7
70%	3.8	4.0	4.2	3.7	3.9	4.1	3.6	3.8	4.1
80%	4.1	4.3	4.6	4.0	4.2	4.5	3.9	4.1	4.4
85%	4.2	4.5	4.8	4.1	4.4	4.6	4.1	4.3	4.5
90%	4.4	4.7	4.9	4.3	4.5	4.8	4.2	4.4	4.7
95%	4.6	4.8	5.1	4.5	4.7	5.0	4.3	4.6	4.8
96%	4.6	4.9	5.1	4.5	4.7	5.0	4.4	4.6	4.9
97%	4.7	4.9	5.2	4.5	4.8	5.0	4.4	4.6	4.9
98%	4.7	5.0	5.3	4.6	4.8	5.1	4.5	4.7	5.0
99%	4.8	5.0	5.4	4.6	4.9	5.2	4.5	4.8	5.0
99.9%	4.9	5.2	5.6	4.8	5.1	5.4	4.7	4.9	5.3

Grade	-1%			0%			1%		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	3.0	3.2	3.4	3.0	3.2	3.4	3.0	3.1	3.3
60%	3.3	3.5	3.7	3.2	3.4	3.6	3.2	3.4	3.6
70%	3.6	3.8	4.0	3.5	3.7	3.9	3.5	3.6	3.8
80%	3.8	4.1	4.3	3.8	4.0	4.2	3.7	3.9	4.1
85%	4.0	4.2	4.4	3.9	4.1	4.3	3.8	4.0	4.2
90%	4.1	4.3	4.5	4.0	4.2	4.4	3.9	4.1	4.3
95%	4.2	4.5	4.7	4.1	4.3	4.6	4.1	4.3	4.5
96%	4.3	4.5	4.7	4.2	4.4	4.6	4.1	4.3	4.5
97%	4.3	4.5	4.8	4.2	4.4	4.6	4.1	4.3	4.5
98%	4.3	4.6	4.8	4.2	4.5	4.7	4.1	4.4	4.6
99%	4.4	4.6	4.9	4.3	4.5	4.8	4.2	4.4	4.6
99.9%	4.5	4.8	5.1	4.4	4.7	5.0	4.3	4.5	4.8

Grade	2%			3%			4%		
Reliability	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain	Clear	Very Light Rain	Rain
50%	2.9	3.1	3.3	2.9	3.1	3.2	2.9	3.0	3.2
60%	3.2	3.3	3.5	3.1	3.3	3.5	3.1	3.2	3.4
70%	3.4	3.6	3.8	3.3	3.5	3.7	3.3	3.5	3.6
80%	3.6	3.8	4.0	3.6	3.7	3.9	3.5	3.7	3.9
85%	3.7	3.9	4.1	3.7	3.9	4.0	3.6	3.8	4.0
90%	3.9	4.0	4.2	3.8	4.0	4.2	3.7	3.9	4.1
95%	4.0	4.2	4.4	3.9	4.1	4.3	3.8	4.0	4.2
96%	4.0	4.2	4.4	3.9	4.1	4.3	3.8	4.0	4.2
97%	4.0	4.2	4.4	3.9	4.1	4.3	3.9	4.0	4.2
98%	4.1	4.3	4.5	4.0	4.2	4.4	3.9	4.1	4.3
99%	4.1	4.3	4.5	4.0	4.2	4.4	3.9	4.1	4.3
99.9%	4.2	4.4	4.7	4.1	4.3	4.6	4.0	4.2	4.5

## CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Compared to the clear weather conditions, the changes can be summarized as follows: (a) driver dilemma zone boundaries start farther from the stop line by approximately 0.2 second from the time of arrival at the intersection; (b) driver PRTs increase in wet roadway surface and rainy weather conditions by approximately 0.11s (15%); and (c) driver deceleration levels decrease in wet roadway surface and rainy weather conditions by approximately  $0.30\text{m/s}^2$  (8%).

Using models developed for driver PRT and deceleration levels stochastic yellow timings were computed. The results demonstrated that for higher precipitation levels, longer yellow interval durations are required. For the three precipitation levels used in the study, the required increase in yellow interval timing from clear conditions to wet roadway surface conditions is between 4 to 7 percent and the required increase for rainy conditions ranges between 9 and 15 percent. Higher speed limits and lower roadway grades require longer yellow duration times and the increase in percent of yellow interval durations decreases as roadway grades increase. The differences of yellow interval timing between different weather conditions indicates the importance of implementation of specific clearance intervals for inclement weather to reduce red light running, rear-end collisions and right-side-swipe crashes. Consequently, the change of yellow interval durations for different weather conditions can be integrated within the VII. Combined with the impacts of driver gender, driver age, roadway grade, approach speed and TTI, it is possible to provide customizable driver warnings prior to a transition to a red indication (e.g. customized in-vehicle warnings to drivers).

The focus of the study was on the design yellow intervals for passenger cars travelling under wet roadway and rainy weather conditions. It is anticipated that more severe inclement weather conditions (such as snow, freezing rain, ice and fog) would further impact driving behavior with reduced visibility, reduced vehicle traction, increased stopping distances and uncertainty of other motorists behaviour. It is recommended that future field testing should be conducted to study the impact of severe roadway conditions, adverse weather conditions, traffic flow density, and heavy duty vehicles on the design intersection clearance times.

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